# Relationship between vegetation biophysical properties and surface temperature using multi-sensor satellite data

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**Abstract.**

Vegetation is an important factor in global climatic variability and plays a key role in the complex interactions between the land surface and the atmosphere. In this study, we focus on the spatial and temporal variability of vegetation and its relationship with land-atmosphere interactions. We have analyzed vegetation water content (VegWC), leaf area index (LAI), and normalized difference vegetation index (NDVI) and land surface temperature (Ts) from Advanced Microwave Scanning Radiometer for EOS (AMSR-E) and Moderate Resolution Imaging Spectroradiometer (MODIS). We have selected three regions which have climatically differing characteristics: the North America Monsoon System (NAMS) region, the South Great Plains (SGP) region, and Little River Watershed in Tifton, GA. Temporal analyses were performed by comparing satellite observations from 2003 and 2004. The introduction of normalized vegetation water content (NVegWC) derived as the ratio of VegWC and LAI corresponding to the amount of water in individual leaves has been estimated and this yields significant correlation with NDVI and Ts. The analysis of the NVegWC and NDVI relationship in the above listed three regions displays a negative exponential relation, and Ts and NDVI relationship (TvX relationship) is inversely proportional. This correlation between these variables is higher in arid areas such as NAMS regions, and becomes less correlated in the more humid and more vegetated regions such as the areas of Eastern Georgia. A land cover map is used to examine the influence of vegetation types on the vegetation biophysical and surface temperature relationships. The regional distribution of vegetation reflects the relationship between vegetation biological characteristics water and the growing environment.

## 1. Introduction

It has been long recognized that atmospheric and land surface processes are correlated with each other. Climate and meteorological processes determine land surface characteristics such as vegetation distribution, energy balance, and watershed hydrology (Neilson, 1986; Lu *et al*., 2001; Small and Kurc, 2003; Weiss *et al*., 2004). Land surface processes in turn affect atmospheric temperature and humidity, precipitation and radiative transfer (Pielke *et al*., 1998; Lu *et al*., 2001, Weiss *et al*., 2004). Various studies have dealt with these interactions, including the development of land-atmosphere models (Noilhan and Planton, 1989; Pitman, 1991; Xue *et al*., 1991) and the relation of vegetation dynamics to other land and climate variables (Betts *et al.*, 1997; Bounoua *et al*., 1999; Weiss *et al*, 2004).

Meteorological and climatological conditions both impact and are influenced by vegetation distribution and dynamics (Sellers *et al*., 1996; Betts *et al*., 1997; Bounoua *et al*., 1999). For example, the rooting depth of plants varies with climate (Schenk and Jackson, 2002). In turn, rooting depth influences the vertical distribution of water within the soil column and hence transpiration and evaporation (Kleiden and Heimann, 1998; Pielke, 2001). Land cover changes have modified a large portion of the Earth's terrestrial surface and biosphere (Schlesinger *et al*., 1990; Swetnam and Betancourt, 1998), and these changes are often accompanied by changes in the biochemical and biophysical properties of vegetation. It is believed that the anthropogenic changes in land cover affect the local meteorology such as cloud cover, precipitation, surface hydrology, and surface temperature (Pielke *et al*., 1999).

Vegetation has been monitored over broad areas with the development of satellite remote sensing (Nemani *et al*., 1993; Tucker, 1979). Vegetation in these studies has been quantified using normalized difference vegetation index (NDVI), leaf area index (LAI), vegetation water content (VegWC), and other metrics. NDVI and LAI have been used to characterize the type and amount of vegetation that exists (Zeng *et al.*, 2000) and to evaluate the relationship of vegetation to hydrometeorological variables such as surface temperature (Goetz, 1997). More recently, researchers have attempted to estimate VegWC by introducing satellite-derived variables such as normalized difference water index retrieved in near infrared channels of satellite sensors (Ceccato *et al*., 2001; Zarco-Tejada *et al*., 2003). Vegetation water content for individual plants is a useful measure of a plant's physiological state, especially when coupled with other measurements (Kramer and Boyer, 1995). The utility of remotely-sensed VegWC to describe vegetation processes has not yet been completely evaluated.

The goal of this paper is to examine the relationship of VegWC to other vegetation properties, both spatially and temporally, and to provide a statistical analysis of the relationship between vegetation properties and surface temperature. The physical properties of vegetation described by satellite-derived NDVI, LAI, and VegWC are examined seperately for different vegetation types. We focused on the summer season (June to September), corresponding to the period of maximum vegetation activity in the regions analyzed.  We examined the following three basic research questions:

(1) Higher leaf area index is equivalent to more leaf layers, implying more water is stored in plant

canopies. Do LAI and VegWC co-vary, and if so what is the nature of the relationship?

(2) Are plants that have high water content greener than those with low water content?

(3) Surface temperature tends to decrease as NDVI increases, as summarized by the TvX relationship (Goetz, 1997). Does surface temperature also decrease as VegWC increases?

The paper is organized as follows. Section 2 is a detailed description of the satellite remote sensing data sets and the study regions. Section 3 includes a description of the analyses corresponding to each of the three research questions listed above. The major conclusions of this work and outstanding issues are discussed in Section 4.

## 2. Data and Methods

### 2.1. Study Regions

Three regions have been selected to examine the spatial variations of the land surface variables [Figure 1]; (1) the North American Monsoon System (NAMS) region; (2) South Great Plains (SGP) region, and (3) Little River Watershed in Tifton, Georgia. The NAMS region has been the focus of numerous studies on the interactions between meteorology, vegetation, and land surface fluxes (Kurc and Small, 2004; Weiss *et al*., 2004). Generally the onset of the North American Monsoon occurs in June or early July and continues into September (Weiss *et al*., 2004). The SGP region has also been studied to compare the climatic changes to that of the NAMS region (Weckwerth *et al*., 2004). The SGP region with the onset of the monsoon in this region shows climatically contrasting changes. The southern great plains, for example, receive more precipitation than the NAMS region, but the rainiest months are in the spring rather than the summer. The decrease in plains rainfall is generally concomitant with the onset of the NAM (Weckwerth *et al*., 2004). For the atmospheric research related with surface moisture in the SGP region, the International $H_2O$ Project (IHOP) has been undertaken since 2002 (Weckwerth *et al*., 2004). The Little River Watershed region around Tifton, Georgia as one of the highly vegetated regions in east coast areas has been a subject for soil moisture research. This region has a humid climate and denser vegetation than the NAMS and SGP regions. Because of the short-term but very frequent rainfall events in summer, it has large inundated areas with mixed forests (Bosch *et al*., 1999). The satellite data have been processed in equal-sized areas (500 km×500 km) for those study regions, and they are referred to as follows: NAMS region, IHOP region, and Tifton, GA. The geographic latitude and longitude of their center points are 33.5N and 107.5W, 36.5N and 100.0W, and 32.4N and 84.0W, respectively. Figure 2 shows typical climatic trends of the three regions. The NAMS region is relatively dry with relatively low vegetation amount. Major types of vegetation in this region are shrublands with limited grasslands and crops. The IHOP region, in contrast, shows relatively more humid climate with more vegetation which is grasslands, crops, and limited trees. Tifton, GA is highly vegetated with mixed forest (*e.g.* pines and hardwoods) and crops (*e.g.* peanuts and cotton), showing wet and humid climate with highly frequent rainfalls.

2.2. Moderate Imaging Spectroradiomter (MODIS)

MODIS has been designed for the needs of global change research with improved capability for terrestrial satellite remote sensing (Justice et al., 1998). There are two multi-instrument satellites of MODIS: Terra and Aqua, launched on December 18, 1999 and on May 4, 2002, respectively. These satellites, which are sun-synchronous polar orbiting, pass from north to south across the equator at 10:30am (Terra) and at 1:30pm (Aqua). MODIS provides 44 global data products for land, ocean, and atmospheric variables with 36 spectral bands between 0.405 and 14.385µm. Its spatial resolution at nadir is 250m (band 1~2), 500m (band 3~7), and 1000m (band 8~36) (Justice et al., 1998, and Justice et al., 2002). The algorithms of the MODIS land data are available at the MODIS website (http://modis.gsfc.nasa.gov), and we downloaded the land data (NDVI, Ts, LAI, and Land Cover Map) from the Land Processes Distributed Active Archive Center website (http://edcdacc.usgs.gov) for this study.

NDVI is a biophysical parameter that quantifies the photosynthetic activity of vegetation by observing the 'greenness' of the vegetation which is related to the chlorophyll abundance and energy absorption (Tucker, 1979; Myneni *et al*., 1995). NDVI has been widely used for various studies on dynamic land surface changes such as deforestation and drought and as an important variable to model simulations such as land surface hydrology and land-atmosphere interactions. NDVI is used to compute various biophysical variables such as biomass and green cover (Huete et al., 2002). NDVI is derived using the normalized ratio of the red and near infra-red surface reflectances (Tucker, 1979).. In this study, we have used MODIS Terra 16-day aggregated NDVI data sets at 1km spatial resolution.

The distribution of vegetation cover on global and continental scales has been investigated in many studies from satellite derived data and field measurements (Defries *et al*, 1998; Hansen *et al*, 2000). The MODIS land cover map uses all available spectral, temporal, directional, and spatial information from other MODIS data sets (Friedl *et al*., 2002). The land cover maps have been a very important tool for global and continental scale studies of climate and biogeochemistry, and NDVI and LAI have been important variables to derive these land cover maps (Myneni *et al*., 2002). Land cover maps derived from MODIS were used in this study and follow the International Geosphere – Biosphere Program (IGBP) classification for land cover types (Friedl *et al*., 2002). Table 1 provides the land cover units with accompanying descriptions.

MODIS also provides surface temperature (Ts), which is derived from thermal infrared data (Justice *et al*., 1998; Wan and Li, 1997). Surface temperature is an important variable linking evapotranspiration (ET) to soil moisture availability. Lower soil moisture and ET yield higher surface temperature and greater sensible heating of the atmosphere (Small and Kurc, 2003). LAI is defined as the one sided green leaf area per unit ground area in broadleaf canopies and as the projected needle leaf area in coniferous canopies (Myneni *et al*., 2002). LAI affects the fluxes of energy, mass, and momentum between the surface and the planetary boundary layer (Justice *et al*., 1998). The MODIS LAI products used in this study are derived using radiation models by surface reflectance measurements (Justice *et al*., 1998; Myneni *et al*., 1997).

### 2.3. Advanced Microwave Scanning Radiometer for Earth Observing System (AMSR-E)

The AMSR-E instrument on the NASA EOS Aqua satellite provides global passive microwave measurements of terrestrial, oceanic, and atmospheric variables for the investigation of global water and energy cycles (Njoku et al., 2003; Kawanishi et al., 2003; Shibata et al., 2003). The satellite is in a sun-synchronous orbit with equatorial crossing at approximately 0130/1330 LST. The instrument measures brightness temperatures at six frequencies, 6.92, 10.65, 18.7, 23.8, 36.5, and 89.0 GHz, with vertical and horizontal polarizations at each frequency, for a total of twelve channels. The incidence angle is fixed at 54.8°, altitude of 705 km and the AMSR-E provides a conically scanning footprint pattern with a swath width of 1445 km. The mean footprint diameter ranges from 56 km at 6.92 GHz to 5 km at 89 GHz. The AMSR-E observed brightness temperatures at the 6, 10 and 18 GHz are used in conjunction with a radiative transfer model to simultaneously retrieve the surface soil moisture, Ts and VegWC. The radiative transfer model is run in an iterative fashion and these three variables are adjusted until the simulated brightness temperatures at the three channels match closely with the AMSR-E observed brightness temperatures at the same location (Njoku et al., 2003). The algorithm derived VegWC, soil moisture and Ts global daily data is stored at the National Snow and Ice Data Center (NSIDC) website (http://www.nsidc.org/data/amsre). We acquired VegWC data from this web site for our study regions and the time period of interest. Based on the algorithm, VegWC is retrieved from a radiative transfer model in which vegetation opacity is used to derive VegWC at low frequency (Njoku and Li, 1999). The AMSR-E VegWC possibly has biased data values particularly on water bodies and bare soil areas. AMSR-E VegWC is derived from surface roughness parameter incorporating effects both of vegetation and roughness (Njoku *et al.*, 2003; Njoku and Chan, 2005). Since roughness and vegetation have similar trends in their effects on the normalized polarization differences, the algorithm assumes the surface roughness parameter as VegWC (Njoku and Chan, 2005). However, this assumption is acceptable only for smooth surface with vegetation. For example, a non-zero VegWC value in a desert area is only due to surface roughness. To avoid this error, we selected study regions primarily not including any water bodies and bare soil areas, and assumed that the selected regions have smooth vegetated surface and are not affected by any surface roughness other than vegetation.

### 2.4. Data processing and analysis

All MODIS data sets used in this study have a 1km spatial resolution while AMSR-E data is at 25km with a different map projection type. Thus, in this study all data sets had to be re-sampled to be consistent with each other. All 1km MODIS data were converted to 25km resolution as AMSR-E data, and the different spatial projection types between MODIS and AMSR-E were changed to the same AMSR-E geographical projection. The nearest neighbor method has been used to change the spatial resolutions and the projection types. Then each data set has been averaged for the 3-month summer season (June $9^{th}$ to September $12^{th}$). When data sets are re-sampled, errors are inevitable. To minimize this error, we removed the cloud-contaminated MODIS data pixels based on the data retrieval quality information provided for every pixel and then analyzed the standard deviation for each process.In addition, we exclusively considered natural vegetation types (from 1 through 10 in the IGBP classification) for this analysis of the variables with the land cover types. Permanent wet lands are possible to have contaminated retrieval especially for VegWC as it is mentioned in the section 2.2, and croplands should be considered more with the effects from human activity as well as climatic effects. Correlations between the variables were analyzed by linear or other regression methods, and especially in the relationships between any three variables, color coding, for example, Ts versus NDVI for different land cover types for easy recognition and analysis.

2.5. Normalized Vegetation Water Content (NVegWC)

Asymptotic relationship between NDVI and LAI has limited application to direct relationships between the variables (Clevers 1989; Carlson and Ripley, 1997). In Figure 3, NDVI shows rapid increase with LAI in low NDVI areas. The slow NDVI-increase region in this regime has been accepted due to a surface almost fully covered by leaves (Curran, 1983), and these asymptotic thresholds in which NDVI is saturated vary with vegetation type, age, and leaf water content (Paltridge and Barber, 1988). Moreover, Ceccato *et al*. (2001, 2002b) found that NDVI and VegWC did not co-vary in a simple fashion, which may be attributed to differences between biomes in contrasting climatic regimes. A decrease in chlorophyll content, which is considered to reflect a decrease in NDVI, does not directly indicate a decrease in VegWC and vice versa. It is obvious that larger vegetation structures will have higher vegetation water content. In order to examine the indirect relationships between the variables, we propose a new variable, the Normalized Vegetation Water Content (NVegWC) defined as VegWC per unit plant leaf area (the ratio of VegWC and LAI), which is linked with the leaf water conservation mechanism.. Our intent with calculating NVegWC was to facilitate a biome-to-biome comparison of vegetation water content and its relationship with other variables such as NDVI.

**3. Results**

Figure 4 shows distributions of each variable for the three regions for 2003 and 2004, and every pixel in each box is at a re-sampled 25km spatial resolution as mentioned above. Annual variation is not significant, showing similar distribution patterns in the study regions, but typical regional distributions can be simply observed from the figure: arid areas with relatively low vegetation like the NAMS region and high Ts and humid areas with relatively high vegetation and low Ts like the Tifton, GA.

3.1 The relationship of VegWC with NDVI and LAI (Research Question 1 and 2)

Figure 5 shows the relationship of VegWC with NDVI and LAI for each study region. This relationship for each study region reflects its general climatic characteristics. These relationships can be generalized to the fact that VegWC varies less with low NDVI or LAI especially in the NAMS region, and with the increase of NDVI or LAI, the variation of VegWC is higher. VegWC in its relationship with NDVI and LAI shows very similar distributing patterns in the NAMS and IHOP regions, but in Tifton, GA the variation of VegWC with LAI is much greater then that with NDVI. Considered with the asymptotic relationship between NDVI and LAI mentioned in the section 2.5, Figure 5(a) shows the NDVI saturation zone around 0.8 in Tifton, GA, indicating that most vegetation shows maximum NDVI during the summer season in Georgia area.

NVegWC, the ratio of VegWC and LAI, is noticeable in its relation with NDVI. Figure 6 shows relatively strong relationship especially in the NAMS region with high R-square values. A general description of this relationship is high NVegWC with low NDVI. It is also remarkable that these statistical correlations become weaker in a more humid environment like Tifton, GA. This indicates that vegetation in more arid or semi-arid areas is more dependent on water condition of its environment. Figure 7 shows the NVegWC variation range for each land cover type. Even in the same vegetation type, NVegWC variations are different in each region, and the average values in the NAMS region are generally higher with wider variation range while Tifton, GA shows much less variation of NVegWC with lower average values than the other regions. The major types of vegetation in the NAMS region (shrublands and savannas) show relatively high NVegWC with very high variation. Thus, the negative exponential relationship between NVegWC and NDVI in Figure 6 can be explained as the tendency of vegetation behavior, which is high water-leaf vegetation with low NDVI.

3.2. The relationship between Ts, NDVI, and NVegWC (Research Question 3)

We investigated how surface temperature varies with NDVI and VegWC. Figure 8 shows (a) General description about the relationship between Ts and NDVI (or vegetation greenness) and (b) the relationship diagrams for the study regions. This relationship, termed as the TvX relationship, has been examined in many previous studies as a fundamental descriptor of the land surface state related with surface moisture availability and hence ET (Nemani and Running, 1989; Sandholt *et al*., 2002). The geometry of the TvX relationship shows regional, climatic and biome dependence (Goetz, 1997; Sandholt *et al*., 2002), and our study regions fall within the triangle-shaped geometry, showing a good contrast of general climatic and vegetation characteristics in each study region. The clustering of the points from each of the three regions on the TvX plot shows the importance of climate and vegetation characteristics. The TvX relationship of the NAMS region in the figure is distributed in the range of upper and left area, which indicates very low vegetation and dry condition with high evaporation. The IHOP region in this relationship shows relatively wetter climate than the NAMS region with more partial canopy. Tifton, GA, on the other hand, shows fully vegetation and very wet climate with high transpiration. With low evaporation, Ts of bare soil is much higher than that of plant canopies, and therefore a negative slope exists along the dry or warm edge. This slope in the TvX relationship is steeper in dryer conditions (Goetz, 1997; Nemani *et al*., 1993). In Figure 9, the steepness of the negative slopes is higher in the NAMS region.

Through the regression analyses of the TvX relationship, the statistical correlation in the NAMS region is much stronger, compared with Tifton, GA. NVegWC has been color-coded into this TvX relationship in Figure 9, showing high NVegWC distributed in higher Ts and lower NDVI areas. With the negative exponential relationship between NVegWC and NDVI explained in the previous section, this analysis also supports our finding that more water exists in vegetation leaves of more arid environments. Arid regions with low NDVI, however, do not have a continuous canopy cover but a sparse coverage, for example, clumps of vegetation interspersed with bare soil area. Since Ts of bare soils is always larger than that of transpiring vegetation in summer season, Ts of the NAMS region is higher than that of the other two regions, considered in this study (the Figure 8 and 9). Because of this influence of discontinuous vegetation coverage on Ts, the relationship between NVegWC and Ts in such arid areas can be overstated, but the NVegWC – NDVI relation provides enough clues for the conclusions reached in this study.

## 4. Discussion and Conclusion

We have performed analyses of four land surface variables (VegWC, NDVI, LAI, and Ts) to investigate their interactions, using satellite derived data of AMSR-E and MODIS. Spatial variation of the relationship between them has been mainly focused through selecting three climatic characteristic regions in North America: the NAMS region, the IHOP region, and Tifton, GA. Each region shows typical trends of arid or semi-arid and humid areas. During these analyses, we introduced a new variable, NVegWC, and obtained remarkable results. The negative relationship between NVegWC and NDVI and between Ts and NDVI shows more water existence in plant leaves in more arid area, and the determination coefficients for those relationships of each region in the regression analyses explain the dependency of vegetation on water condition. It is generally assumed that the greenness of vegetation is related to the photosynthesis and the photosynthesis is dependent on solar radiation and the amount of carbon dioxide. Water content in vegetation is also utilized for the photosynthesis by which oxygen is released into the atmosphere, causing plant transpiration. Water amount in vegetation is closely related to different vegetation types than the greenness of vegetation which is considered as an indicator of photosynthesis. The photosynthesis process in vegetation is controlled under water stress condition. There are many physiological and climate factors influencing vegetation water stress such as soil moisture and precipitation, and that the surface temperature is one of the indicators of increased water stress.During the summer months, an increase in Ts implies an increase in water stress of vegetation, all other factors being equal, and moreover in arid regions Ts is more likely to impact water stress of vegetation than other factors. Vegetation physiologically responds to high water stress condition by closing the stomata to control losing moisture and by having a deep and widely-spread root system to reach water sources in deeper soil (Tanguiling et al., 1987; Cohen et al., 2005). There are also some species, especially in arid area, that store more water in leaves during rainy season (Kramer, 1983). Weighing actual amount of water in different plant types separately for leaves, stems, and fruits/flowers, Sims and Gamon (2003) showed that in drought deciduous shrubs contain more water in their leaves than that in evergreen tree leaves These physiological responses of vegetation have been considered as adaptation mechanism to environment (Kramer, 1983), and they would be present more in vegetation in arid regions where the water stress is a normal situation. Hence, the dominant vegetation in arid area like the NAMS region is more likely to be adapted to their environment in a way to minimize their water loss than that in more humid area like Tifton, GA. In this study, LAI shows significant regional difference in values (NAMS : 0~2, IHOP : 0.5~2.5, Tifton, GA : 1.5~6), but the regional differences of VegWC values between the three regions is not as much (NAMS : 0~3 $kg/m^2$, IHOP : 1~4 $kg/m^2$, Tifton, GA : 1~4 $kg/m^2$). This can be explained as vegetation amount varies significantly under the regional climate condition, but the vegetation response shows a tendency to conserve water.

The definition of VegWC derived from AMSR-E, however, is area-averaged water content in the vertical column of vegetation overlying soil ($kg/m^2$) (Njoku and Li, 1999). The surface roughness is related to the vegetation opacity, and this determines VegWC under the assumption of uniformly vegetated surface in a unit area. This approach is derived from a linear relationship between vegetation opacity and vegetation water content (Jackson and Schmugge, 1991; Le Vine and Karam, 1996). Hence, VegWC can be also defined as total water mass in vegetation per unit ground area, including leaves as well as stalks and branches. Unlike VegWC, LAI does not represent the whole plant in vegetation but only leaves. Thus, NVegWC derived as the ratio VegWC and LAI should be interpreted carefully because it can be overestimated as actual water content per unit leaf. However, this study is significant in that this provides general information about physiological behavior of vegetation against its environment in a more regional scale. Remote sensing or ground-based observation data about accurate water amount in different parts of vegetation for spatial analyses in more global scales are required for more accurate research in various spatial scales. Further research about this phenomenon with the relation to plant photosynthesis and the variation of the amount of carbon dioxide amount in the near plant-atmosphere will support this study.

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